Optimisation of Battery Energy Storage Capacity for a Grid-Tied Renewable Microgrid

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***Abstract*—There are various hurdles in using Renewable microgrids that have to be dealt with such as intermittency of output power as well as reliability of the system. Battery energy storage has been widely addressed as a solution to overcome the limitations of renewable energy resources. Besides, it effectively enhances the system performance and maximises economic profit. Therefore, optimal sizing of battery energy storage is a crucial task at the design stage to reduce operational cost and increase the system reliability. The aim of this paper is to propose a practical approach to achieve the optimal capacity of energy storage for a grid-tied renewable microgrid through peak shaving and energy saving techniques. However, if the system is designed to satisfy critical loads, the load profile has the most prominent influence on the battery sizing. Once the size of the battery energy storage is determined, two different scenarios are defined to verify the effectiveness of the proposed technique. In this paper, the renewable-microgrid system comprises wind turbine, solar panel, battery storage and a backup diesel generator in case of critical load presence. The problem is analysed throughout a year with 24 time steps for each day. The results confirm the effectiveness and functionality of the method from the cost minimisation and optimal operation perspectives.**

Keywords*—*Sizing Optimisation, Battery Energy Storage Systems, Battery Sizing, Microgrid, Renewable Energies

I. INTRODUCTION

Recently, there have been remarkable efforts on harvesting renewable energies and integrating them to generate electricity as they are pollution free and social friendly [1]. However, in order to address the economic, and reliability concerns whilst meeting the required energy demand, it is essential to construct a secure infrastructure by deploying innovative theories and techniques to overcome the restrictions of these resources [2], [3]. Depending on the available resources, a combination of two or more types of renewable energies may be used in a renewable microgrid (RMG) in order to improve reliability and efficiency of the system [4]. The RMG systems are designed to operate either standalone or grid connected. The isolated RMGs are suitable for remote areas where the access to the power grid is not feasible or electrification cost is expensive. On the other hand, the main purpose of using grid-tied RMG systems is to mitigate the electricity bill and provide a more secure power system in outage contingencies [5]. The time-variability of renewable resources such as wind and solar power hampers the RMG to achieve their maximum potential. Battery Energy Storage Systems (BESS) play a crucial role in such systems as they absorb surplus energy as long as the energy carriers are available and inject the energy into the load whenever it is required [6]. Peak shaving is regarded as another significant advantage to the RMG system equipped with BESS. When it comes to peak shaving, electrical loads are categorised into two types including flexible and uncontrollable loads [7]. The controllable load can be shifted to off-peak times for the purpose of peak shaving. By contrast, the peak shaving in RMGs with uncontrollable loads is merely performed through BESS [8]. Therefore, using BESS along with RMGs turns the uncertain renewable resources into dispatchable ones. Besides, the BESS improves the reliability of the system and brings economic advantages. However, this component can significantly increase the investment cost of the system and therefore, selecting the proper capacity is a delicate task [9] and various features from technical and economical aspects should be taken into consideration. From the economic perspective, it is aimed to reduce the investment cost of BESS, maintenance cost, and the electricity bill [7]. This has led to forming BESS optimisation problem. In the literature, various techniques to obtain the optimum size of BESS have been reported such as artificial intelligence, iterative, and analytical approaches, each one of which takes different constraints and parameter into account to determine the size of the BESS as elaborated in [10]. Depending on the available information and the desired operational and economic criteria to meet the requirement of the system, technique can be combined with each other to achieve a precise result. For instance, a double-layer optimisation has been introduced in [11], in which the authors employed a Mesh Adaptive Direct Search (MADS) optimisation approach as the outer solver and Improved Particle Swarm Optimisation (IPSO) as the inner solver for a RMG system consisting of wind turbines, solar panels and microturbine generators [11]. Nevertheless, combining these approaches will lead to more complexity and longer optimisation time.

On the other hand, the iterative approach investigates all possible configurations for a given RMG based on the load profile and operational and economic constraints of the components. In this method, the size of each component is linearly varied to find a solution that meets the operational expectations of the system [10]. Once a feasible configuration is identified, it will be economically compared with other possible solutions to decide whether it grants the maximum

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benefit or not whilst satisfying the operational requirements of the system [12]. The authors adopted the iterative technique in [5] to determine the size of the component in a grid-tied system comprising a photovoltaic system and BESS. Afterwards, the computed possible configuration is economically evaluated by the means of indices such as Excess Power Ratio (EPR) to achieve the optimal solution [5].

In the literature, the energy saving has been solely considered as the main contributing element in profit and the cost associated with peak demand which has a tremendous impact on the BESS size, has been neglected. However, in this study, a practical BESS sizing method based on the benefit resulted from both peak shaving and energy saving using the historical load profile has been proposed. This approach satisfies the BESS sizing problem criteria from technical and economical perspectives. In section II, the model and characteristics of the components utilised in the MG are discussed in details. In section III, the elements associated with battery cost and the proposed algorithm to calculate the optimal size of the BESS are expressed. Section IV discusses about applying the proposed techniques to two different scenarios in order to perform cost analysis and evaluate the effectiveness of the method. The last section concludes the paper according to the obtained results.

II. The Microgrid Component Model and Characteristics

The proposed renewable energy system encompasses the following componentry; wind turbine, PV panels, and a BESS which are linked to the utility grid (grid-tied system) through converters to satisfy the energy demand and a backup generator to cover up the generation deficit during outage.

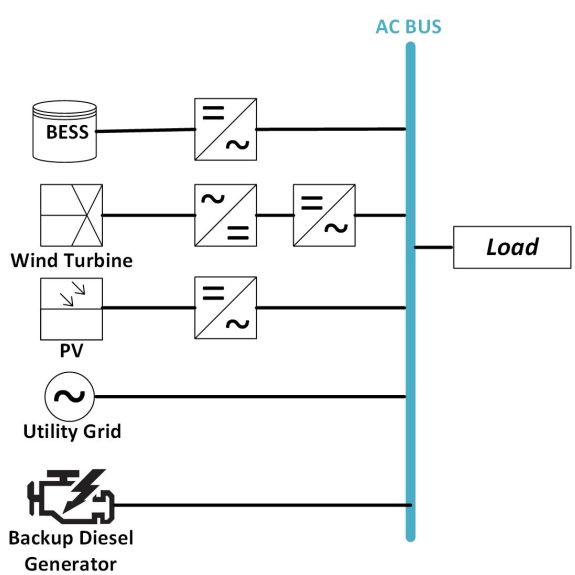

Figure 1. The basic structure of a renewable microgrid system with backup generator

The importance of backup generators is revealed when dealing with critical loads, that require continuous supply, a diesel generator might be considered to meet the load demand in emergency occasions. The conceptual architecture of this system is illustrated in Fig. 1. The BESS not only can improve the RMG performance and reduce the electricity bill by employing an scheduling optimisation approach, but also supplies the load for a certain period during outage contingencies.

A. Photovoltaic Model

The generated electricity at the output of PV panels and wind Turbines are in accordance with the solar irradiation and wind speed profiles. The generated power of PV arrays ($P_{out_{PV}}$) is usually defined as a function of PV efficiency and solar radiation and given by (1). The effect of temperature fluctuations on the output power of PV arrays have been neglected in this study [5].

$$P_{out_{PV}}(t) = N_{PV}.\eta_{PV}.S.I(t) \tag{1}$$

where N_{PV}, η_{PV}, S, and $I(t)$ are number of panels, efficiency of PV panels (%), the area of a PV array (m^2) and $I(t)$ the instant solar radiation, respectively.

B. Wind Turbine Model

The available power at the output of a Wind Turbine (WT), denoted as $P_{out_{WT}}(t)$, is dependent upon wind velocity and is often described as a piecewise function as in (2).

$$P_{out_{WT}}(t) = \begin{cases} 0 & v(t) \leq v_{ci} \\ 0 & v_{co} \leq v(t) \\ N_{WT}.P_{rated}.\frac{v_{(t)}^k - v_{ci}^k}{v_{rated}^k - v_{ci}^k} & v_{ci} \leq v(t) \leq v_{rated} \\ N_{WT}.P_{rated} & v_{rated} \leq v(t) \leq v_{co} \end{cases} \tag{2}$$

where P_{rated} denotes the rated power at rated wind speed v_{rated}. v_{ci} and v_{co} are the upper and lower marginal wind speed range at which the WT generates power and k is the shape factor in Weibull distribution used for wind energy characterisation [13].

C. BESS Model and Constraints

The BESS is commonly modelled based on its energy status at each time step and its operational constraints. There are maximum and minimum limitations for charged and discharged energy as well as charge and discharge power rates that should be within certain ranges as indicated in (3). Besides, charging and discharging cannot be happening simultaneously. Therefore, the step function $U(t)$ is defined and multiplied to the charging and discharging powers to avoid this as in (3).

$$\begin{gathered} 0 \leq P_{charge}(t) \leq P_{max}^{charge}.U(t) \\ 0 \leq P_{discharge}(t) \leq P_{max}^{discharge}.(U(t)-1) \\ E_{BESS(Min)} \leq E_{BESS}(t) \leq E_{BESS(Max)} \end{gathered} \tag{3}$$

where $P_{charge}(t)$, $P_{discharge}(t)$, $E_{BESS}(t)$ represent charging power and discharging power rates at each instant time, respectively. $E_{BESS}(t)$ is the remained energy in the BESS at time t. The initial and ultimate charge of the BESS should be equal in a complete cycle which is commonly considered to be 24 hours as stated in (4) [1], [6].

$$\sum_{t=1}^{24}(E_{charge}(t) - E_{discharge}(t)) = 0 \quad (4)$$

The generic dynamic model of energy transfer in a BESS is described as in (5).

$$E_{BESS}(t+1) = E_{BESS}(t).\beta - E_{discharge}(t) + E_{charge}(t)$$
$$\beta = (1 - \delta_{BESS}) \quad (5)$$

$$E_{discharge}(t) = \frac{P_{discharget}(t)}{\eta_{discharge}}.\Delta t \quad (6)$$

$$E_{charge}(t) = \eta_{charge}.P_{charge}(t).\Delta t \quad (7)$$

where Δt implies the time interval. (5) defines the energy of the BESS at the next time step $E_{BESS}(t+1)$ as a function of its energy level $E_{BESS}(t)$, discharging energy $E_{discharge}(t)$ and the charging energy $E_{charge}(t)$ at the present time. (6) and (7) define the discharged and charged energy at time interval Δt respectively. η_{charge}, $\eta_{discharge}$, and δ_{BESS} indicate the charging efficiency, discharging efficiency, and the energy loss ratio of the storage correspondingly.

D. Load Characteristic of Building G39-Griffith University

Energy demand is intrinsically a time dependant variable as it fluctuates greatly during the day and different seasons due to external factors such as weather condition changes [14]. In order to cover all these fluctuations, electricity demand for a period of a year is considered in this study. The sampling time is opted to be 1 hour to take the hourly load variations into consideration. Therefore, there exist 8760 time steps for the whole period to be examined for the purpose of BESS. In this study, the load is uncontrollable and peak demand can not be shifted to an off-peak time. Therefore, peak shaving is only achievable through scheduling the operation of BESS. The actual commercial load profile was collected from building G39 at Griffith University. As it is clear from Fig. 2, the peak demand does not go beyond 200 kW except for two days when it reached to 202 kW.

Fig. 2(a) shows the peak load demand value for each day which represents how gradually the demand varies in different seasons, whereas Fig. 2(b) illustrates the maximum hourly demand over the period of one year. As it can be concluded from these figures, the minimum demand during the day is around 7 am and the demand before 8 am is as nearly half as load demand between 10 am to 8 pm and thereafter, the demand has dropped again.

E. Technical Specifications of Components

The proposed WT is a vertical axis type which can generate 5 kW power at its rated speed 5 [m/s], with a cut-in and cut out wind speed of 3.5 [m/s] and 15 [m/s], respectively. In order to meet the load demand and in accordance with the wind potential of the location, 4 WTs with a total power capacity of 20 kW are going to be installed. Considering the effective available area and the load demand profile, a PV module consists of 317 polycrystalline type panels manufactured by Canadian Solar with a nominal power of 320 W for each panel to generate a total power of 100 kW has been proposed.

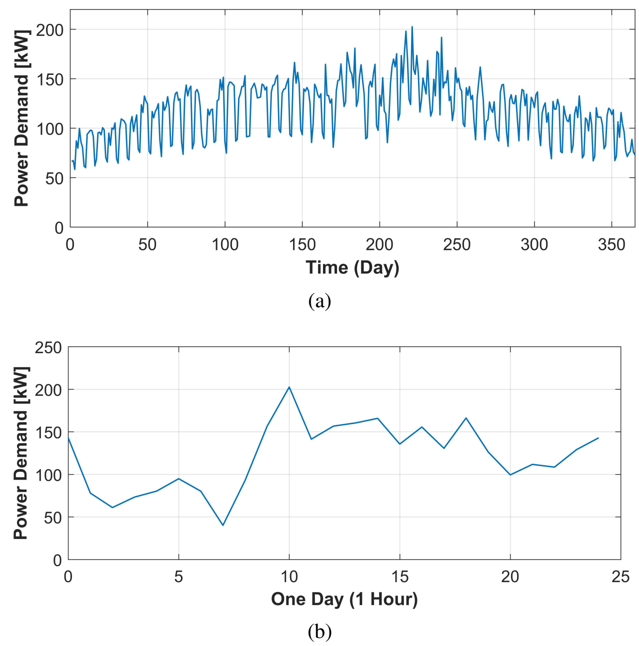

Figure 2. The peak load demand variations throughout a year (a). Maximum load demand at every hour for a year (b)

III. Proposed BESS Sizing Method

The primary criteria for battery sizing in island RMGs is to meet the load demand during the the time when renewable resources are unavailable (days of autonomy). Therefore, they often require higher battery capacity as compared to the grid-connected RMGs [5]. However, in grid-tied systems, the BESS is employed for the purpose of cost reduction through shaving the peak demand as well as storing the redundant generated power and selling it at the most profitable time.

Nevertheless, if the load of the RMG is critical, the power supply should be maintained all the time. Therefore, it is necessary to determine the BESS capacity so that it could supply the load for a certain time to protect the operating devices and create the abundant time for backup generator to start up. The worst scenario occurs when neither renewable resources nor electricity grid are available. Another significant factor contributing in BESS sizing problem is battery cost minimisation. The BESS cost mainly includes installation cost and maintenance cost. The purchase and installation cost are one-time costs whereas maintenance cost is an annual parameter and is maintained for the whole life time period of the BESS. Taking the Capital Recovery Factor (CRF) into consideration, the total cost of BESS (TC_{BESS}) can be calculated through (8) and (9).

$$CRF = \frac{Ir.(1+Ir)^{LT}}{(1+Ir)^{LT} - 1} \quad (8)$$

$$TC_{BESS} = \Big(FC.CRF + \sum_{y=1}^{LT}(C_{Maintenance}.\alpha_y)\Big).C_{BESS} \quad (9)$$

where Ir, LT, $C_{Maintenance}$, FC, C_{BESS}, and α_y are interest rate, life time of the BESS, maintenance cost, one-time cost, the capacity of the battery bank, and inflation rate for maintenance cost, respectively.

The electricity provider companies charge their customers for the highest demand within a month in \$/kW and the annual saved cost from peak shaving is denoted by APSS. The Annual Total Benefit (ATB) can be found using (10). The APSS is obtained within 12 month (m) and the benefit from saving energy is achieved for 365 days (d) and 24 time slices (t) per day. Although the benefit increases as the peak decreases, there is trade-off between benefit and TC_{BESS}.

$$APSS = \sum_{m=1}^{12} \Big(max(P_{m_{BPS}}) - max(P_{m_{APS}}) \Big).Trf_P$$
$$ATB = \sum_{d=1}^{365} \Big(\sum_{t=1}^{24} Trf(t)_E.P_{discharge}(t).\Delta t \Big) + APSS \qquad (10)$$

where $P_{m_{BPS}}$, $P_{m_{APS}}$, Trf_P, and $Trf(t)_E$ are peak of demanded power before peak shaving, peak of demanded power after peak shaving for an individual month, the energy tariff at time instant (t), and peak tariff, respectively.

The Payback Period (PBP) is defined as the time period which takes for the BESS to return its invested cost and thereafter till the end of life time period, it makes profit. The PBP is dependent on the annual profit resulted from employing BESS which encompasses two components: the annual profit from energy savings and peak demand reduction. The PBP can be found using (11).

$$PBP = \frac{\sum_{y=1}^{LT} \Big(ATB.Ir_y \Big)}{TC_{BESS}} \qquad (11)$$

The proposed iterative algorithm determines the optimum BESS capacity based on the two aforementioned costs as illustrated in Fig. 3. Initially, the load profile, solar radiation, and wind speed profile are used to calculate the generated power at the output of PV and WTs using (1) and (2), respectively. Then, the initial capacity of BESS is set to 0, meaning that the RMG is without BESS. The load is primarily supplied by the generated power from renewable resources and the remaining load demand is satisfied through the grid and BESS. Therefore, the demanded load that our algorithm is dealing with is $\Delta P_{load}(t)$.

$$\Delta P_{load}(t) = P_{load}(t) - P_{PV}(t) - P_{WT}(t) \qquad (12)$$

It is assumed that the BESS is fully charged at the initial state. The proposed method detects the peak values during the day and shaves them at each iteration until the BESS reaches to its depth of discharge (DOD) value using (5). Since the BESS can have a full cycle of charge and discharge as discussed in (4) and the discharge of BESS occurs during peak hours, it is charged during off-peak hours. This procedure continues for all days of the year and consequently the monthly peak values are effectively reduced. Once the iteration for a year is completed, the BESS capacity is incremented by a BESS capacity step (ΔC_{BESS}) and the whole process is repeated all over again till it reaches to the determined maximum BESS value. Finally, the maximum total benefit for all possible BESS values are calculated and plotted against BESS capacity variations and the optimum BESS size can be concluded.

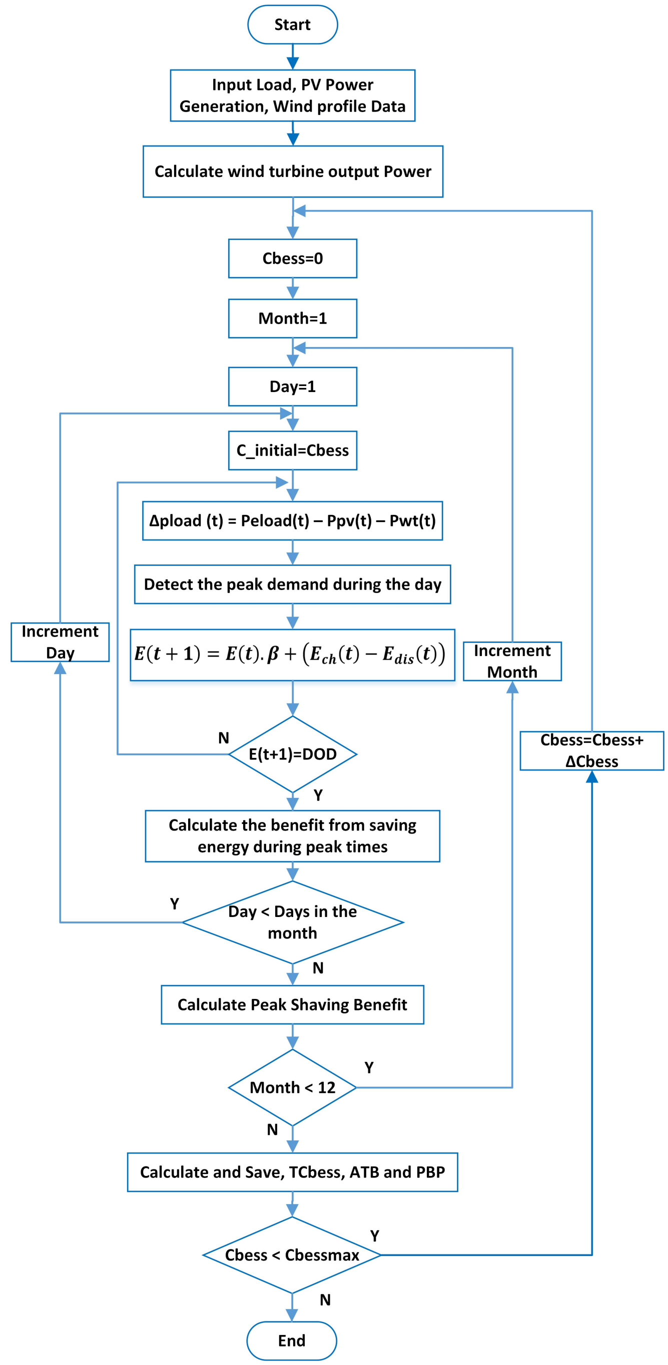

Figure 3. Flowchart of the algorithm to achieve the optimal size of the BESS

IV. Case Studies and Cost Analysis

The hourly output power of WT and PV are achieved from wind speed and solar radiation profile acquired from the available weather station installed at Griffith University-Gold Coast Campus. At the design stage, it is desired to install 4 WTs with the specifications mentioned in section II. Fig. 4 represent the estimated PV and WT power calculated from (2) and (14) and the load demand variations on a typical day. The actual load profile was achieved from building G39 located at Griffith University-Gold Coast Campus. The load of this building is regarded as commercial load according to the application of the building.

There are two main dynamic pricing policies imposed by electricity distribution companies including Real Time Pricing (RTP) and Time of Use (TOU) tariffs[15], their advantages and disadvantages of which are discussed in [16]. In this study, the TOU scheme is adopted as the commercial buildings are charged by the grid. However, neither of these polices affect the underlying concept of proposed approach. The TOU plan defines certain time periods namely as peak and off-peak times and each one of which has its corresponding price. In Queensland state, customers are charged 9.7 ¢ per kWh during the peak time (between 7 am to 8 pm) and 6.6 ¢/ kWh over the off-peak period (from 20 pm to 7 am). The monthly peak cost is about 24$ per kW.

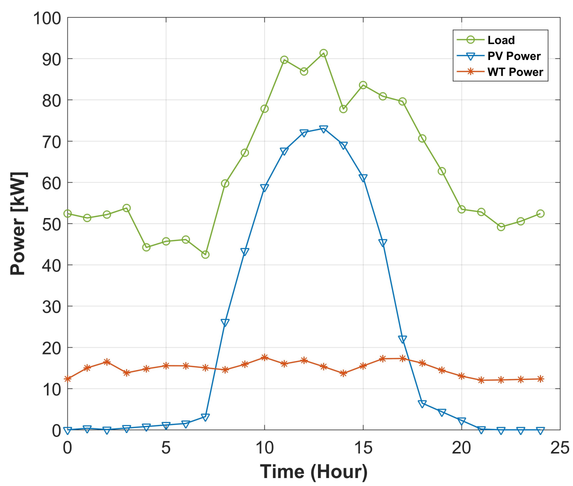

Figure 4. The generated power by PV and WTs and load demand on a typical day

The interest rate is assumed to be 5% and the battery life time is 8 years. The one-time cost for the proposed Lithium-ion battery is estimated about 600$ per kWh and its annual maintenance cost is approximated to be 20$ per kWh. The charging power rate, discharging power rate, and depth of discharge are selected as 20 kW, 15 kW and 10% C_{BESS}, respectively. The Total Benefit (TB) for the whole life period of the battery can be found using (13). The TB consists of annual total benefit minus BESS maintenance and investment cost. TB is in $ and the minimum BESS capacity is set at 0.

$$TB = LT \times (ATB_{LT} - MC_{LT} - FC) \tag{13}$$

A. Scenario A: Critical Load

As explained in section III, it is desired to determine the BESS so that it could be able to satisfy the load over a certain time (autonomous time period) in worst situation. The worst case scenario occurs when the power grid and renewable power are unavailable for any possible reason. At this situation, those loads which are highly sensitive to power disconnection, are vulnerable and therefore, the BESS should back up the load. However, in such systems, it would not be economic if the maximum load demand was considered for battery sizing. The proposed solution in these cases is to hourly average the load within 24 hours for the whole period of collected data which in this case is one year. In this paper, the backup duration for the battery in worst case scenario is determined to be 4 hours as the operating laboratory facilities and equipment in the understudy building take three to four hours to complete the showdown process. Besides, this time period provides abundant time for running and stabilisation of the backup generator. The hourly average demand for a year is calculated as shown in Fig. 5 and the minimum battery capacity for autonomous time ($C_{BESS_{AT}}$) is determined as follows:

$$C_{BESS_{AT}} \geq P_{Av_{max}}.T_A \tag{14}$$

where $P_{Av_{max}}$ and T_A denote the maximum averaged load demand, and autonomous time period, respectively. As it is

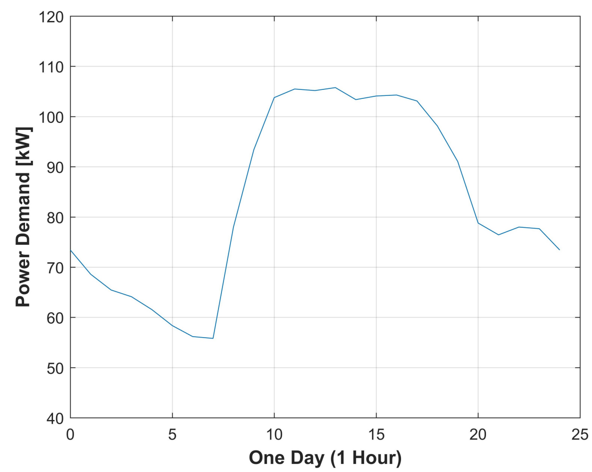

Figure 5. The hourly averaged load demand within one day for whole year

clear from Fig. 5, the maximum averaged power is obtained at 105 kW and therefore the averaged energy demand at the peak for four hours is 420 kWh. This size of battery can guarantee the necessary time window for switching off process of vulnerable equipment and running the backup generator. In this approach, the averaged values have been taken into consideration and not the maximum power demand in an individual day in order to reduce the cost of the battery while assuring that the BESS can cover the load for 4 hours in most of the days and situations.

B. Scenario B: Cost Optimised Battery Capacity

In the second scenario, it is assumed that there is no concern regarding the equipment damage due to power disconnection and rather the economic perspective is regarded as the primary objective of the BESS sizing problem. In this condition, the introduced algorithm is applied to calculate the optimum capacity of the battery bank.

As discussed earlier in section III, the PBP along with total benefit after payback period (TB_{APBP}) are considered as the determinant factors in this scenario. The BESS range is set between 0 to 420 kWh with 5 kWh increment (ΔC_{BESS}) for each iteration to achieve more accurate BESS size. Applying the proposed algorithm on the given RMG, the benefit variation, TB_{APBP}, versus battery capacity changes are achieved as shown in Fig. 6.

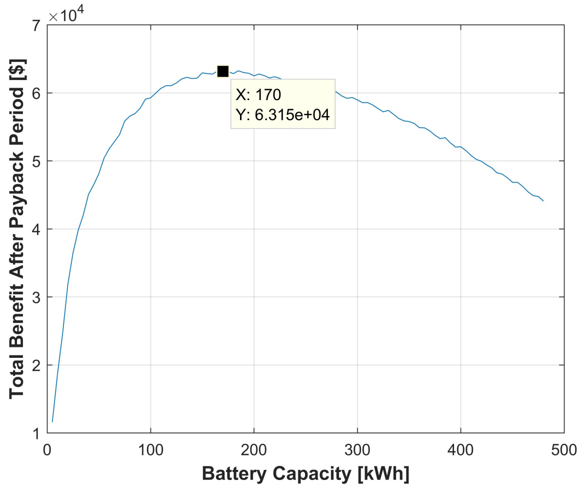

Figure 6. Total benefit after payback period versus capacity changes

The TB_{APBP} increases significantly as the BESS capacity is increased. However, this upward trend starts to slowing down but still ascending till reaches to its peak value. At this point, the BESS capacity at which the maximum achievable benefit for the given RMG configuration is obtained which in this case is equal to 170 kWh and the corresponding TB_{APBP} equals to 63150$. After this point, increasing the BESS acts inversely on TB_{APBP}, because the higher size of the battery, the longer time PBP or in other words, it takes more time to cover the TC_{BESS}.

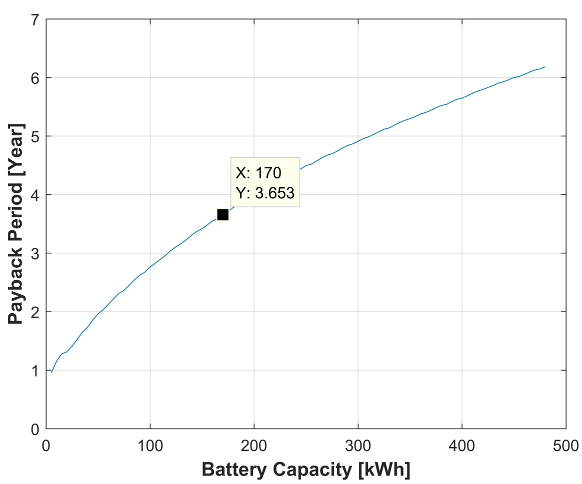

Figure 7. The Payback period versus battery capacity variations

In order to find out the payback time period of the BESS capacity at which the maximum benefit is yielded, the PBP is plotted against BESS size variation as shown is Fig. 7. The payback period is achieved to be approximately 3.5 years and since the battery life time is 8 years, the predicted pure benefit will be counted for 4.5 years.

V. Conclusion

The optimal size of the BESS for a RMG system with regard to economic perspective was determined using the proposed iterative battery sizing method. The proposed BESS optimisation technique was performed for two scenarios. In the first scenario, the hourly averaged load for the whole data period was considered to determine the BESS capacity. In the second scenario, the BESS size was determined by considering the maximum benefit at minimum cost by the means of peak shaving and energy saving techniques during peak times. The proposed algorithm revealed that the TB versus BESS has a peak value at which the BESS capacity is optimum.

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